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INITIATION TO DETONATION OF HIGH EXPLOSIVES BY SHOCKS

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U. S. NAVAL ORDNANCE LABORATORY
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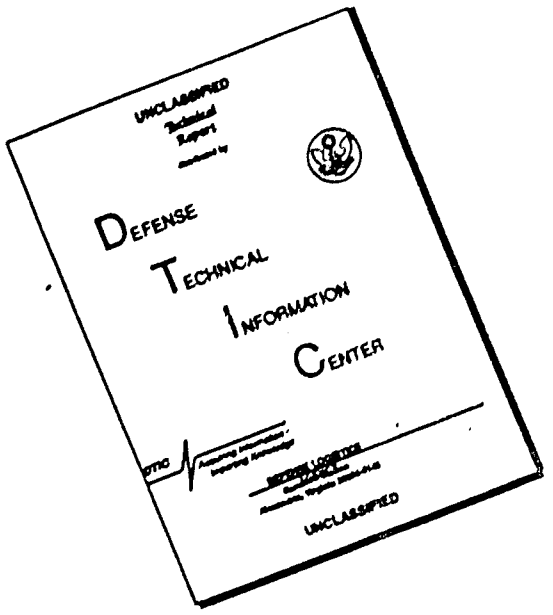

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INITIATION TO DETONATION OF HIGH EXPLOSIVES BY SHOCKS

By:

J. M. Majowicz
S. J. Jacobs

ABSTRACT: A reflected light technique was used to measure the velocity of induced shocks and speed-up to detonation velocity in TNT, Pentolite, Composition B, Composition B-3, 65/35 Octol and 75/25 Cyclotol. The method consisted of placing a light reflecting aluminized Mylar film in contact with the free surface of the test explosive wedge which was fastened to a brass plate, shocking the opposite side of the plate by an explosive detonation and observing with a smear camera the arrival of the shock wave at the free explosive surface. The arrival of the shock was detected by a change in the intensity of light reflected from the Mylar film surface. The initial particle velocity behind the shock front in the test explosive was determined by treating the explosive at the brass surface as an inert material and applying shock impedance relationships. Several points on the Hugoniot were determined for the unexploded explosives from the boundary conditions. Curves are presented for the build-up shock velocity relative to initiation pressure as well as the variation of delay time to steady velocity as a function of induced shock pressure.

EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 5710 1 March 1958

The report presented herein is based on a paper that was given at the AXP Conference held in October 1957 at London, England. The work was done under Task Assignment NOL 260-57 in the Explosion Dynamics Division of the Explosions Research Department. The work described is supported under a task for the University of California Radiation Laboratory to study basic phenomena related to the explosive initiation and detonation processes. This work has interest to workers concerned with deflagration to detonation transition in propellants. The goal of BuOrd Task NOL-323 on Deflageration-Detonation Transition has been augmented by the finding of this report. This work is further useful to Task FR 43 financed with Bureau of Ordnance funds. The results will find application to a key problem concerning the mechanism of initiation of explosives and tests for sensitivity (NAVORD Report 3906: Problem 7.7.7).

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By direction

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INTRODUCTION

The reliable initiation of explosives by shocks weaker than that produced by the steady detonation itself is well known. Examples include: a) initiation by weak boosters (reactive shock), b) initiation by a booster in a can, c) initiation through inert barriers[1,2], and d) initiation by air shock[1,3]. The latter items entail pure shocks. One of the first attempts to unravel the phenomena occurring in the initiation of solid explosives by shock is due to Herzberg and Walker[4,5 p 161]. They found that an explosive appeared to start detonating at a point below the initiator within the body of the explosive (the so-called detonation "hook"). This effect was further studied by Boggs, Messerly and Strecker[6,5 p 161]. The work of these investigators was interpreted by Boggs and by Eyring, et al[5] as a shock propagation phenomena. Herzberg and Walker favored a "low order" detonation hypothesis. More recently Sultanoff[3] studying initiation by air shock found a delay in the time of initiation after the shock impacted the explosive. He also noted the "hook" in the detonation trace. Cotter[7] devised a technique for observing the time interval between initial shocking and emission of light from a transparent explosive (liquid nitromethane) and reported values of the time interval as an initiation time for several values of shock barrier thickness. Recently Cosner[8] showed that detonation of Composition B from a Composition B donor (both charges cylindrical and of equal diameter) whose shock was degraded by a steel barrier appeared to begin at a distance from the barrier-explosive interface and that the distance increased with barrier thickness. The apparent initiation point could be as much as 1 or 2 diameters away from the boundary. This work was independently confirmed by some very beautiful framing camera pictures by Sultanoff[9]. Sultanoff showed that surface displacements occurred on the viewed surface prior to detonation which could be attributed to shocks in the explosion. Cook[10] has shown a number of interesting initiation effects in cylindrical charges. A number of papers related to the subject were presented at the recent "Symposium on the Initiation and Growth of Explosion in Solids" sponsored by The Royal Society (30 May 1956). The authors have seen only the abstracts, however, so no discussion of these will be attempted at this time. Particularly applicable are the

papers by Cachia and Whitbread, Lampson and Eichelberger, and Winning. These are expected to be published in the Proceedings of the Royal Society.

Several hypotheses have been offered to explain the initiation phenomena described above. These include: a) the low order-high order transition apparently first offered by Herzberg (see reference (6) for discussion), b) a non-isotropic propagation of a detonation (shock) as suggested by Boggs, c) some continuous variation in the detonation (shock) rate such as a gradual increase with time (suggested by Boggs). Jacobs[11] revived the latter hypothesis in the light of more recent evidence. To simplify the understanding of the phenomena observed he suggested consideration of a one-dimensional model, Figure 1a. In this model he considered the effect of a square step jump in the boundary velocity produced by a shock entering the explosive through a barrier such as a metal plate. This boundary velocity determines an initial pressure and shock velocity in the explosive. The compressed explosive is adiabatically heated by the pressure jump behind this shock. This increases the reactivity of the explosive and reaction will first start at the boundary. The result of reaction is to increase pressure and temperature to accelerate the reaction rate. The pressure increase propagates as a compression wave which overtakes the shock front. The shock front velocity is then speeded up. The higher velocity shock causes the material to be hotter than it would have been had the shock not been reinforced. By this process of shock reinforcement, reaction rates mount at increasing distance from the boundary until the reaction time approaches that in a normal detonation. The shock velocity will then stabilize to normal detonation velocity. According to this view the shock front may or may not pass through an over driven shock wave (velocity and pressure exceeding Chapman-Jouguet values) depending on the shock properties and reaction kinetics in the explosive. In this model no "low order" velocities are necessary to effect the transition from shock to detonation but such quasi-steady wave could exist at some stage of the progress of the wave. The more general situation confronting the initiation process is an initial shock wave followed by rarefactions at the boundaries of the charge. The competition between reaction effects to strengthen the shock and accelerate further reaction, and rarefaction effects to weaken the shock and slow down reaction are proposed as the general basis for the observations that have been reported.

Except for the work of Cotter the experiments cited have been performed in geometries of charge and barrier which do not lend themself to the simple analysis suggested above. Cotter's work was incomplete in that there was no way of observing the history of the effects of the shock on the explosive between

the time of shocking and the emission of light. His experiments also could not be performed on the non-transparent solid explosives which are of most interest to the military establishments.

In order to test the above theories it was necessary to devise a method whereby explosive could be initiated by a plane wave in which the ensuing boundary velocity would be as constant as possible. Means had to be found to observe shock velocity as a function of distance of travel of the shock from the boundary. In addition a means of determining the shock amplitude at the boundary was desired. Such an experiment has been found. The following report is a preliminary discussion of the experiments and results obtained to the date of this writing.

The reader who is familiar with the work of Walsh and Christian[14] will recognize the experimental method as a variant of theirs. The present method uses surface reflection of an external light source instead of argon flash gaps to detect the wave arrival. In this respect the method is more generally applicable to the precise measurement of shock and free surface velocity. The measurement is essentially independent of amplitude of the wave velocity and therefore can be extended to lower pressures than the method of Walsh and Christian. In addition the detector is essentially massless and therefore less subject to introduction of a perturbation on the result. Six cast explosives have been studied and data is presented to show: a) shock velocity as a function of initial shock strength and distance of travel from the boundary, b) experimental points on the shock Hugoniot for these explosives, c) delay in initiation as defined by time to reach points where final velocity is reached minus time that would have transpired if initiation were instantaneous.

Experimental Procedure

The experimental arrangement, shown in Figure 2, consisted of a 4".5 diameter NOL plane wave booster[12] made with cast pentolite donor and acceptor; a 0".5 x 5".5 square layer of Composition B-3 (fine particle size RDX in TNT) and, finally, an 8" square brass plate (thickness 0".5, 1".0, or 1".5). Attached to the center of the free surface of the brass was an explosive wedge having an angle of 25° to the brass surface (tapering from approximately 0 to 0".59), a length of 1".25 and a width of 1".25. The free surface of the wedge was covered with an aluminized Mylar film*. A brass wedge with a 25° angle, 0".75 x 1".25 was

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*Aluminized Mylar film was procured from: Coating Products Co., 101 West Forest Avenue, Englewood, New Jersey

mounted below the explosive wedge as shown. As indicated in Figure 2, the explosive wedge was placed 0".25 from the edge of a 0".5 x 1".25 groove in the brass plate which was cut at an angle of 25° while the brass wedge was placed 0".125 below the test explosive wedge. In the groove was placed a 0".125 x 0".5 x 1" strip of Lucite to which was fastened a Mylar film of 0".0005 thickness with an aluminized layer surface of 0".0001 thickness adjacent to the brass surface. The Lucite strip was permitted to extend 0".187 beyond the surface. The groove served the purpose of measuring the shock velocity in the brass while the Lucite strip served the purpose of measuring the free surface velocity of the plate by a light reflection method to be described. Adhesion of the film to the Lucite and explosive wedge surfaces was accomplished by wetting the Mylar film and the surfaces with a dilute detergent solution and then applying a rolling pressure to remove the excess solution. The thickness of the wetting agent remaining between the Mylar film and Lucite or explosive was considered to be negligible.

When set for firing, the assembly was arranged so that the three surfaces, namely, explosive wedge, Lucite strip and brass with a polished surface were normal to the optical axis of the rotating mirror smear camera (writing speed, 3.788 mm/μsec). A 3" exploding wire light source[13] was used to illuminate the Mylar covered and polished brass faces. The light source was positioned by projecting the slit of the camera onto the reflecting surfaces and placing the source at a line along the path of the reflected slit image. In the test then, as the shock arrives at the reflecting surface, the direction of the particles in the aluminum layer or polished surface changes with respect to the optical axis of the camera. This in turn brings about a sharp discontinuity or interruption in the character of the reflected light.* The photographic record can then be interpreted to give the precise arrival time of the shock wave along the groove in the brass, along the polished brass surface, along the explosive wedge and finally the arrival time of the free surface along the Lucite strip. The break in the shock velocity-free surface velocity trace established the arrival time of the shock at the upper portion of the brass-test explosive interface, while the trace from the polished surface of the brass wedge established the arrival time of the shock at the lower portion of the brass-test explosive interface. With this information a correction can be made for any existing wave tilt along the

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* This method is a variant of the technique used by T. P. Cotter to obtain initial shock arrival in his experiment. The present method is based on a suggestion by T. P. Liddiard of this Laboratory.

slit. Tilts at right angles to the slit cause no difficulty in interpretation as long as they are small. A sketch of the smear camera record is shown in Figure 2 and an experimental record is shown in Figure 3.

Results

The instantaneous shock velocity at any point along the explosive wedge surface (corresponding to known but varying explosive thickness) was determined by establishing the tangent to the detonation trace at various positions. The resulting velocities were plotted as a function of explosive thickness and are shown in Figures 4-9. The extrapolated zero thickness value for the initial instantaneous shock velocity in the test explosive was used in determining a point on the Hugoniot of the unreacted explosive as described below. Experimental values of initial shock velocity and final detonation velocity are summarized in Table II.

Shock and free surface velocities of the brass plate were determined in all experiments. Free surface velocity was plotted as a function of shock velocity and is shown in Figure 10. The indicated points represent mean values with a spread of about 1%. In addition, free surface velocity was plotted as a function of brass plate thickness and is shown in Figure 11.

Treating the explosive in the wedge as initially inert, its particle velocity is related to that of the brass by the familiar hydrodynamic expression:

$$u_e = u_m \left[\frac{2(\rho_o U)_m}{(\rho_o U)_e + (\rho_o U)_m} \right]; \quad u_m = 1/2\ u(\text{brass surface})$$

ρ_o = Initial density

U = Shock velocity

u = Particle velocity

e = Subscript referring to explosive

m = Subscript referring to metal

TABLE I

Table of Shots and Explosive Compositions

Explosive Cast (g/cc)	Number of Shots for Brass Plate Thickness (in.)		
	0.5	1.0	1.5
Pentolite (ρ = 1.676) 50/50 PETN/TNT	2	2	1
Composition B (ρ = 1.710)(a)	2	1	1
Composition B-3 (ρ = 1.723)(b)	1	2	1
Octol (ρ = 1.787) 65/35 HMX/TNT	2	2	1
Cyclotol (ρ = 1.729) 75/25 RDX/TNT	2	2	1
TNT (ρ = 1.582) (Creamed)	2	2	2

(a) Composition B: 59.5 ± 2% RDX
39.5 ± 2% TNT
1.0 ± .3% Wax

(b) Composition B-3: 59.5 ± 1.0% RDX
40.5 ± 1.0% TNT
(Median Particle diameter of RDX: 65-80 microns.)

TABLE II

Experimental Data

Explosive	Thickness of Brass Plate (in.)	Extrapolated Shock Velocity, U_s, in H.E. (mm/microsec)	Detonation Velocity, D (mm/microsec)	Initial Particle Velocity in H.E. (computed) (mm/microsec)	Initial Pressure in H.E. (computed) (Kb)
Pentolite	0.506	5.25	7.54	1.364	120.3
	0.985	4.90	7.50	1.252	102.8
	1.481	4.52	7.55	1.136	86.1
Comp B	0.505	5.06	7.91	1.368	118.4
	0.982	4.71	7.95	1.257	101.3
	1.480	4.41	7.93	1.137	85.6
Comp B-3	0.505	5.07	7.99	1.366	119.3
	0.992	4.75	7.99	1.251	102.3
	1.480	4.42	8.00	1.135	86.4
65/35 Octol	0.499	5.30	8.17	1.375	130.0
	0.982	4.91	8.18	1.239	108.6
	1.480	4.69	8.16	1.118	93.6
75/25 Cyclotol	0.506	5.22	8.22	1.357	122.5
	0.984	4.95	8.22	1.242	106.3
	1.481	4.67	8.22	1.124	90.8
TNT	0.500	4.89	5.25	1.395	107.9
	0.981	4.65	5.22	1.275	93.8
	1.481	4.47	5.21	1.147	81.1

Knowing the shock velocity and particle velocity of the initially inert explosive, a point on the Hugoniot for this material was determined with the following two hydrodynamic equations:

$$(1)\quad V/V_o = \rho_o/\rho = (U-u)/U$$

$$(2)\quad P = U\,\rho_o\,u$$

V = Specific volume

P = Pressure

Subscript o indicates uncompressed value

Other quantities are as previously defined. The density of brass was taken to be 8.476; explosive densities are shown in Table I. The plotted Hugoniot curves are shown in Figure 12. Extrapolations to zero pressure in Figure 11 are tentative estimates but the initial slope was determined from weak shock measurements[20].

The variation of delay time to steady velocity as a function of induced shock pressure for all explosives except TNT are shown in Figure 13. Delay time in this figure is defined as in reference (3), namely:

T_{delay} = (time to steady velocity) -

(time if steady velocity existed throughout).

The points represent mean values for duplicate experiments with an accuracy of about .01 microsecond. The values for TNT based on the experimentally determined velocity are given in Table III.

Discussion

The work presented above has been but recently completed. Consequently, there has been insufficient time to consider in detail the significance of the results. Some of its significance is clear, however, and these points will be taken up now:

(a) The initial shock velocity is a function of the velocity of the driving surface. This velocity persists at a steady rate. Because the wave is amplitude dependent and assumes its velocity immediately it can hardly be interpreted as a "low-order" detonation. The results favor the shock followed by reaction hypothesis.

TABLE III

Variation of Delay Time as a Function of Pressure in TNT

Initial Pressure in TNT (Kb)	Delay Time* (microsec.)
108	0.084 0.058
93.8	0.240 0.187
81.1	0.272 0.275

* Based on the observed final (low order) detonation velocity of 5.23 mm/microsec. as given in Table II.

(b) The existence of a steady velocity for a finite period prior to speed-up implies that compression waves due to reaction do not start from the boundary immediately (See Fig. 1b). The steady zone is therefore evidence of an induction period (probably thermal in nature) for the chemical reaction. It is expected that further analysis will determine the induction time as a function of the pressure in the step shock.

(c) The "delay-time" is simply the result of the shock build-up process. The transition from shock to detonation proceeds in an orderly way which can be accounted for by straightforward hydrodynamics and reaction kinetics. This experiment furnishes a basis for examining the kinetics of reactions induced by shocks.

(d) The result for TNT shows two deviations from the other substances, first, the delay is less reproducible and second, the velocity levels off at a value below normal detonation velocity. The first observation suggests that reaction rate is sensitive to the physical variations which can occur from charge to charge even though the initial shock velocity is not. This conslusion is also supported by the differences observed between Composition B and Composition B-3. In these explosives the essential difference is the particle size of the RDX and a small percentage of wax.

The low plateau velocity for TNT suggests a true "low-order" detonation. It could be accounted for by a two-step reaction process for TNT. The effect will require further study for its complete understanding.

(e) The evidence favoring an induction period in the initiation of the explosive strongly suggests the existence of the "plateau" or induction zone in the steady detonation as well. Mallory[15] has already inferred this conclusion in his work on detonation pressure in TNT. This report can offer support to his conclusions. It should be possible, by going to higher impacting velocities on the explosive wedge, to extrapolate the results on an induction period to the kinetic conditions existing in the normal detonation. Cotter[7] has already done work along these lines for liquid nitromethane.

(f) The compressed densities in the initial shock computed from the boundary conditions (e.g. $\rho/\rho_0 = 1.369$ at p = 119Kb) for Composition B-3 strongly suggests that in the explosion of the compressed explosives the pressures reached might, for some conditions, exceed those due to the shock in a normal detonation. (The compressed density already exceeds the C-J value of $\rho/\rho_0 = 1.346$, reported by Fickett and Cowan[16].) Pressures in

excess of C-J values could result in a period of over-drive in the transition from shock to detonation. Such overdrives have been observed in gaseous detonation by Gordon[17]*. There is evidence in the results obtained for Composition B-3 that such overdrive did occur for a short period. The records, however, are insufficiently resolved to assign a magnitude and position to this observation. A camera with a higher writing speed should make this possible. Overdrive was evident[21] in a recent report on initiation of single crystals of PETN.

Summary

An experiment is described in which shock velocity in an explosive can be observed in the initial growth stage. The velocity can be determined as a function of initial shock strength and distance or time of travel. The initial shock strength is simultaneously determined. The experimental method is based on observation of phase velocity along a free boundary by a light reflection technique which becomes essentially a massless detector. Many applications of the method other than that used here are suggested. It should be possible, for example, to use the technique in the following experiments:

(a) Equation of state of solids and liquids,

(b) C-J pressure in explosives,

(c) Study of both elastic and plastic waves and their transition pressure in materials similar to iron.

Reported herein are points on the non-reaction Hugoniots and shock velocity vs. distance for six military explosives in common use. The data have been analyzed to obtain initiation delays as a function of initial transmitted pressure into the explosive over a limited range of pressures. It is believed that the results obtained can be applied to interpretation of initiation problems in which other than one-dimensional geometry exists. Observations such as the "hook" in cylindrical charges should be amenable to analysis if one considers rarefaction effects in addition to the results obtained here.

There are a number of variables which warrant further study by the method used. They include:

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* A. K. Oppenheim[18] cites that Turin and Huebler[19] observed high pressure and overdrive in initiation of gaseous detonation. Oppenheim gives a theory aiming to explain the observation.

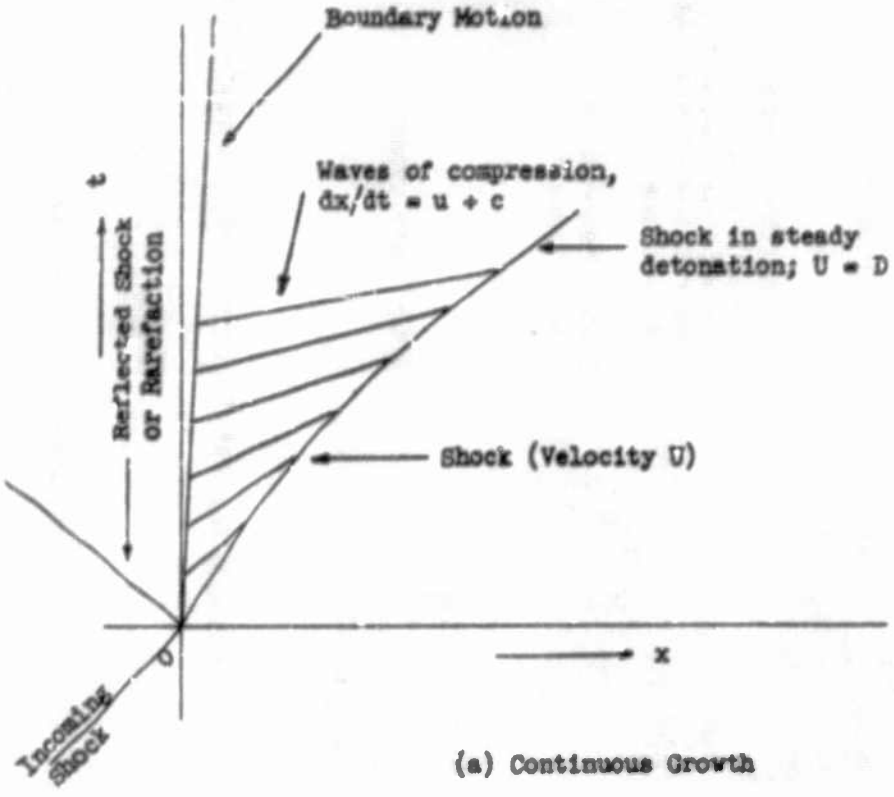
(a) Study of effect of loading density, particle size and additives on initiation.

(b) Extension of the measured range to higher and lower initial shock pressures.

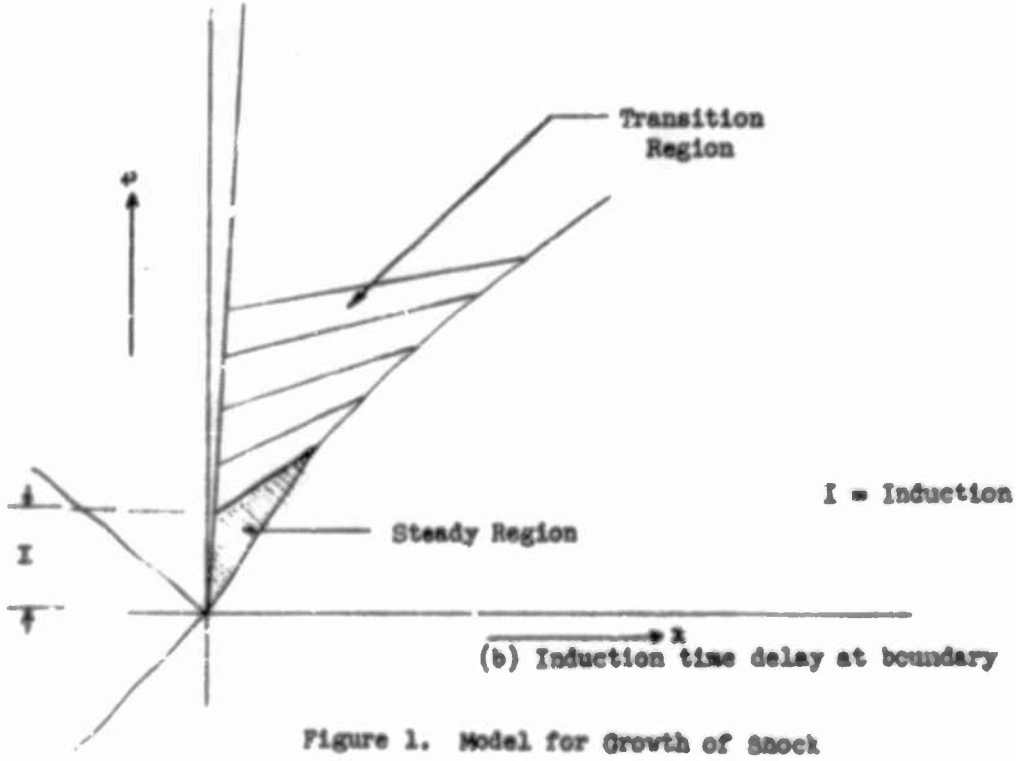
(c) Study of the effect of shocks followed by known rarefaction on initiation transition.

Acknowledgments

The assistance of William Brown and Anthony Valenzino who assembled the charges, set them up and carried out the measurements, is noted with thanks.



(a) Continuous Growth



I = Induction time at boundary

(b) Induction time delay at boundary

Figure 1. Model for Growth of Shock

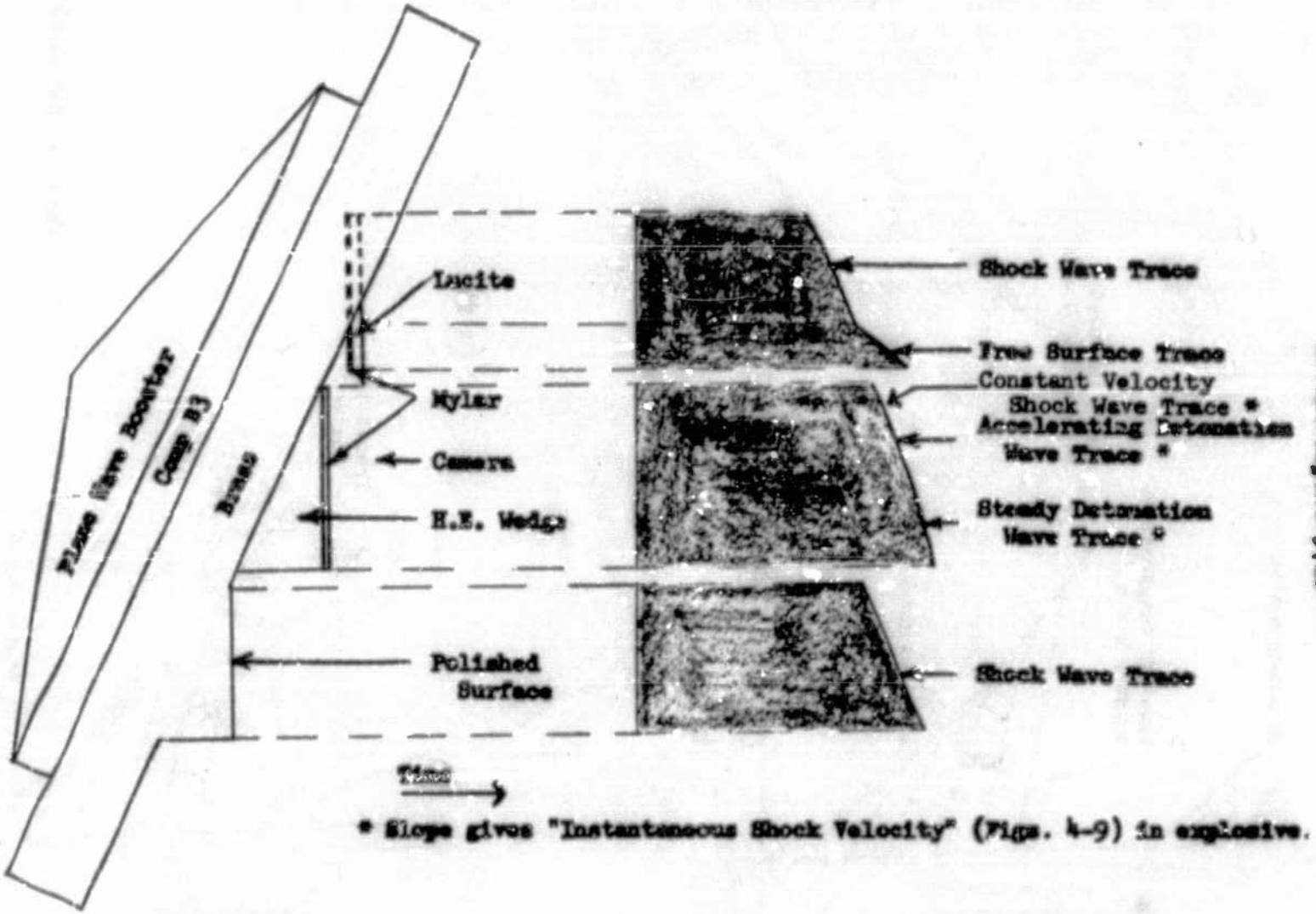


Figure 2. Side View of Explosive System and Sketch of Smear Camera Record.

Figure 3. Smear Camera Record of Comp B-3 Using 1 in. of Brass Plate.

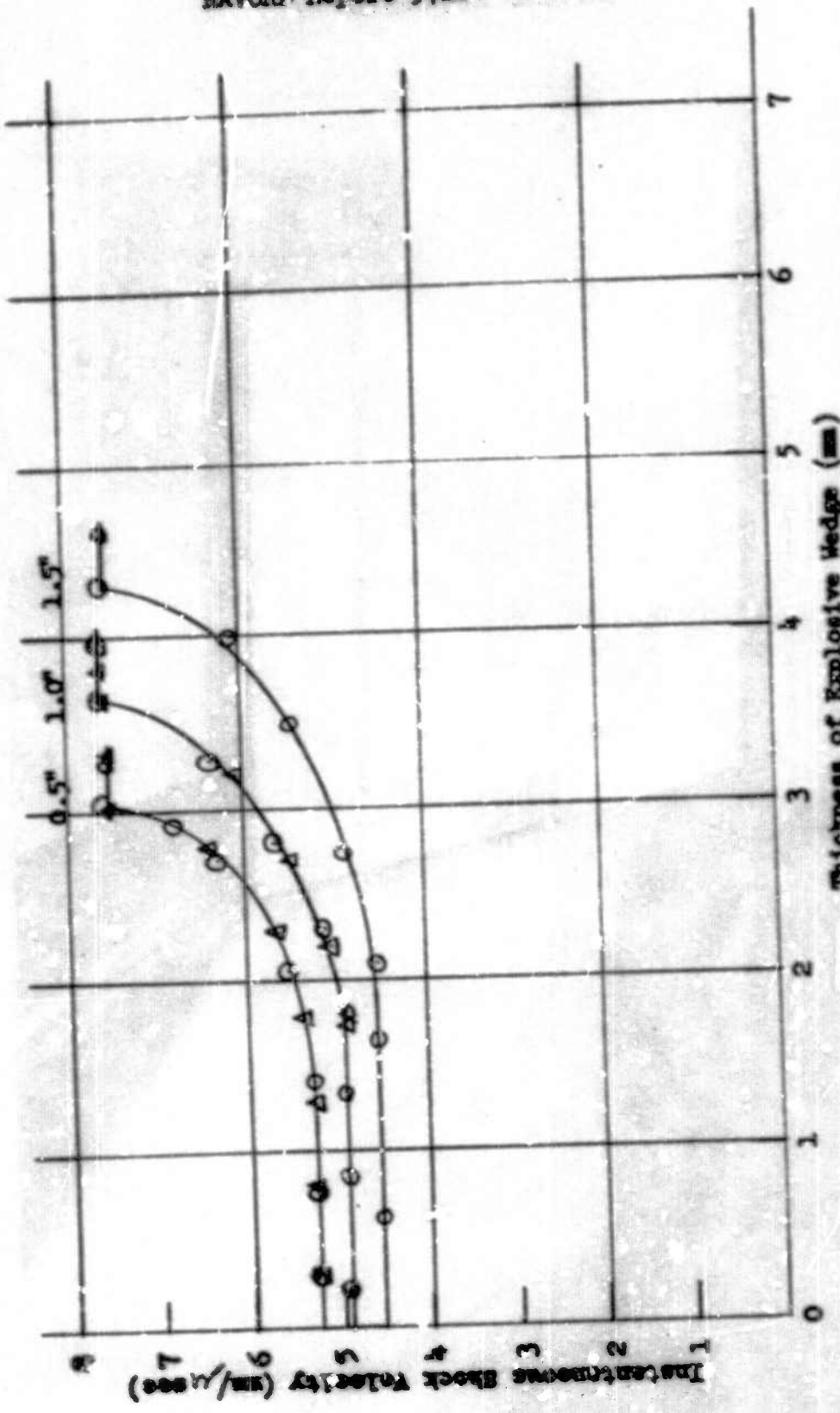


Figure 4. Instantaneous Shock Velocities in Pentolite for three thicknesses of brass.
(Each set of circles or triangles represents an individual shot.)

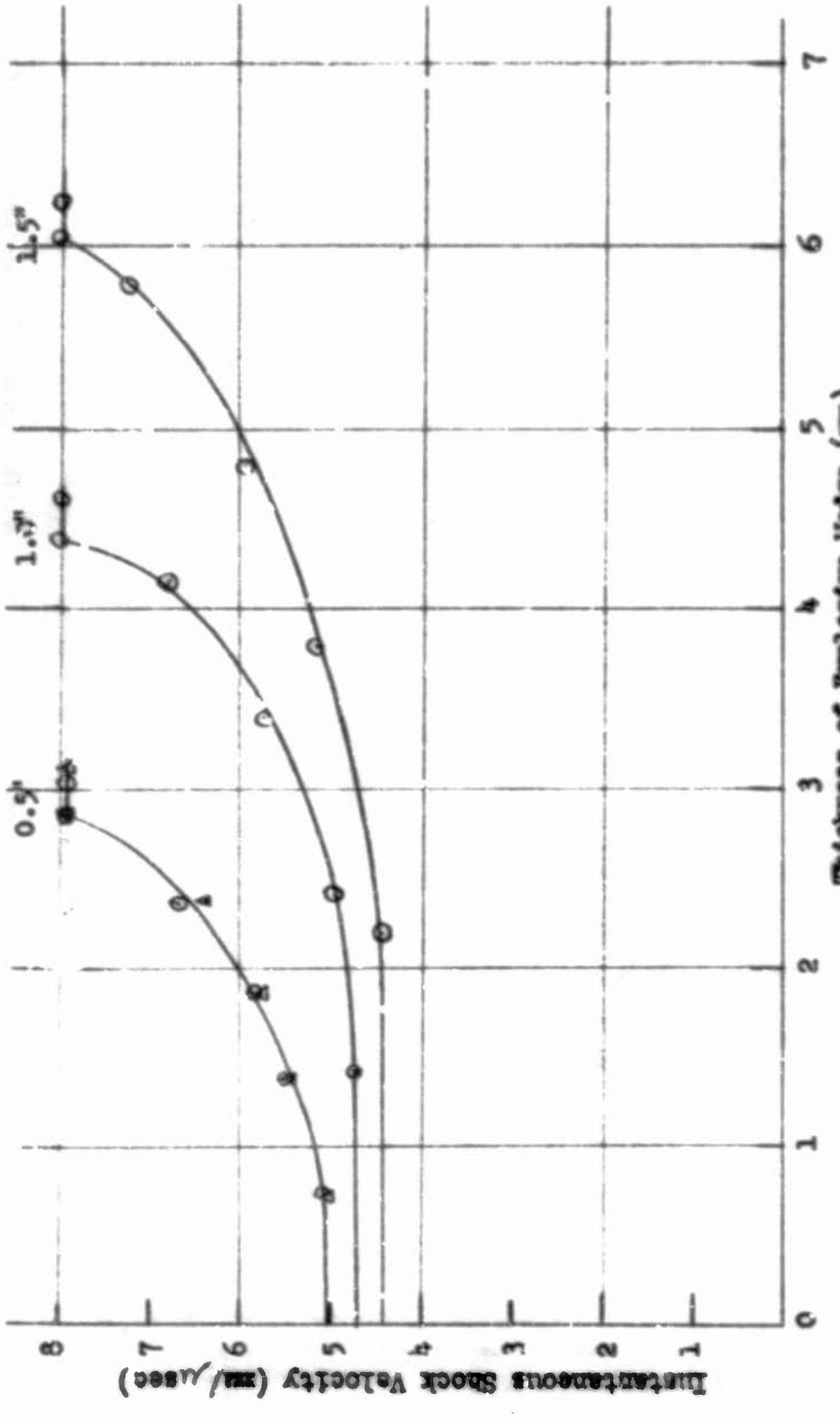


Figure 5. Instantaneous Shock Velocities in Comp B for three thicknesses of brass.
(Each set of circles or triangles represents an individual shot.)

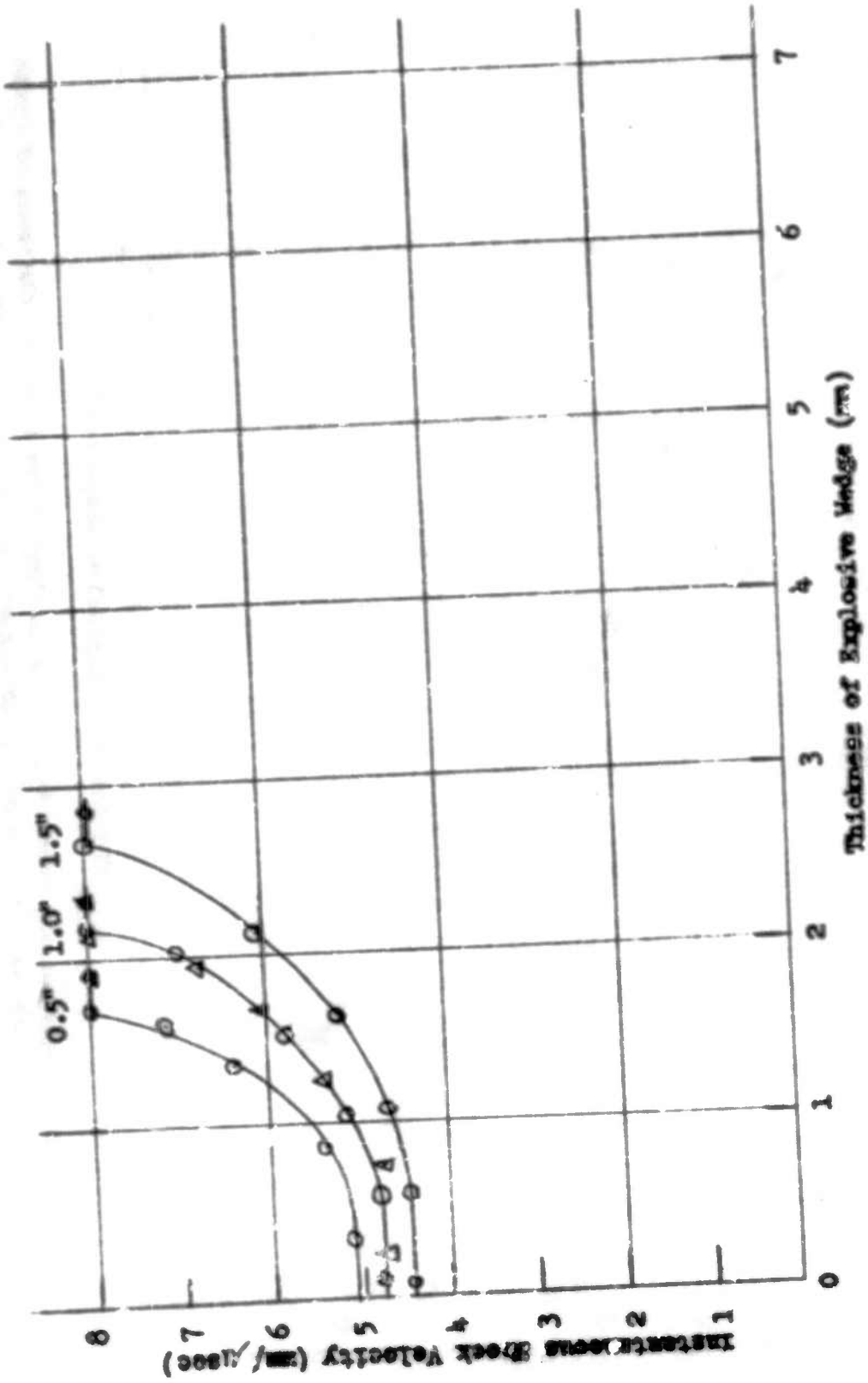


Figure 6. Instantaneous Shock Velocities in Comp B3 for three thicknesses of brass. (Each set of circles or triangles represents an individual shot.)

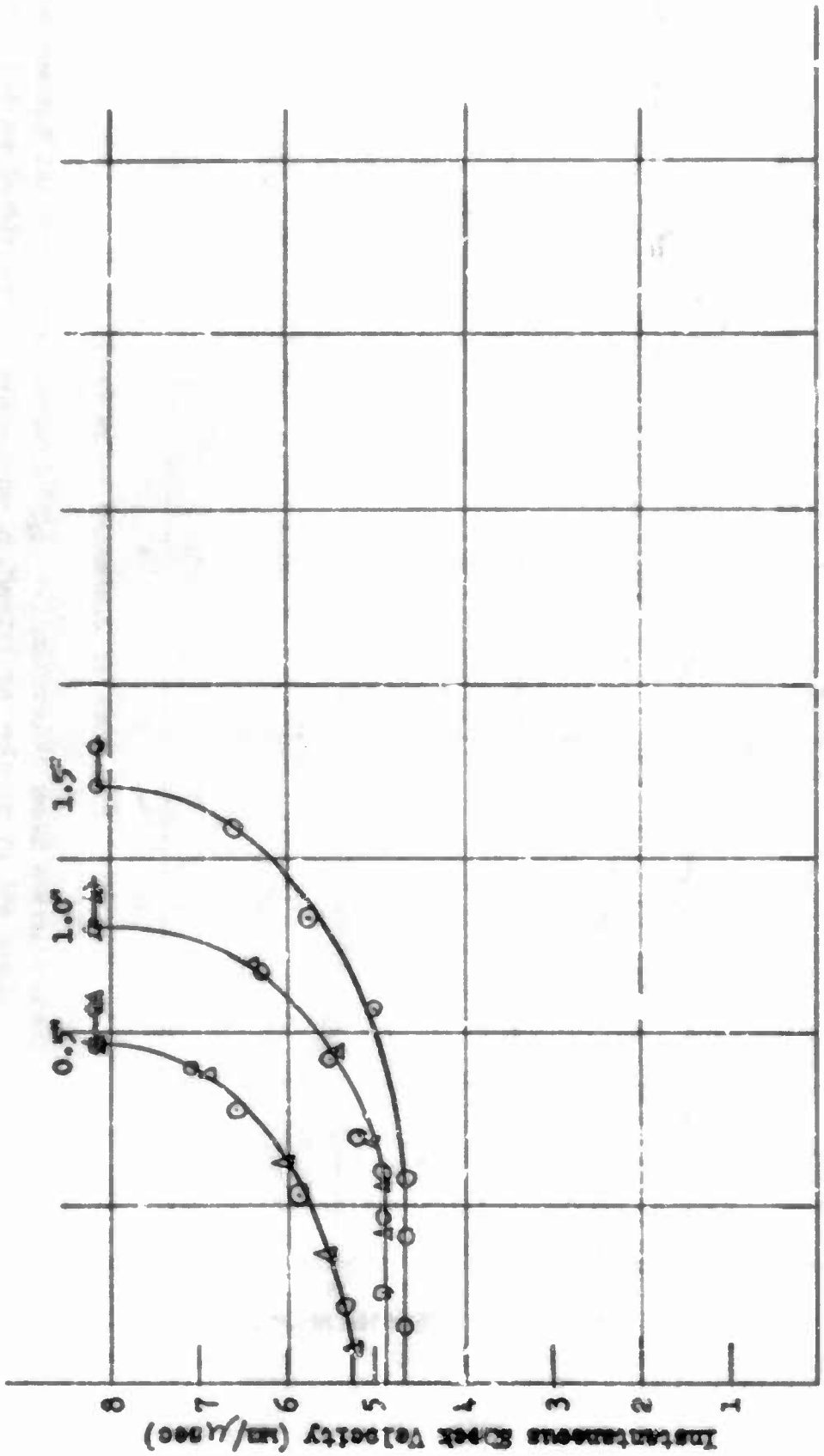


Figure 7. Instantaneous Shock Velocities in 65/35 Octol for three thicknesses of brass. (Each set of circles or triangles represents an individual shot.)

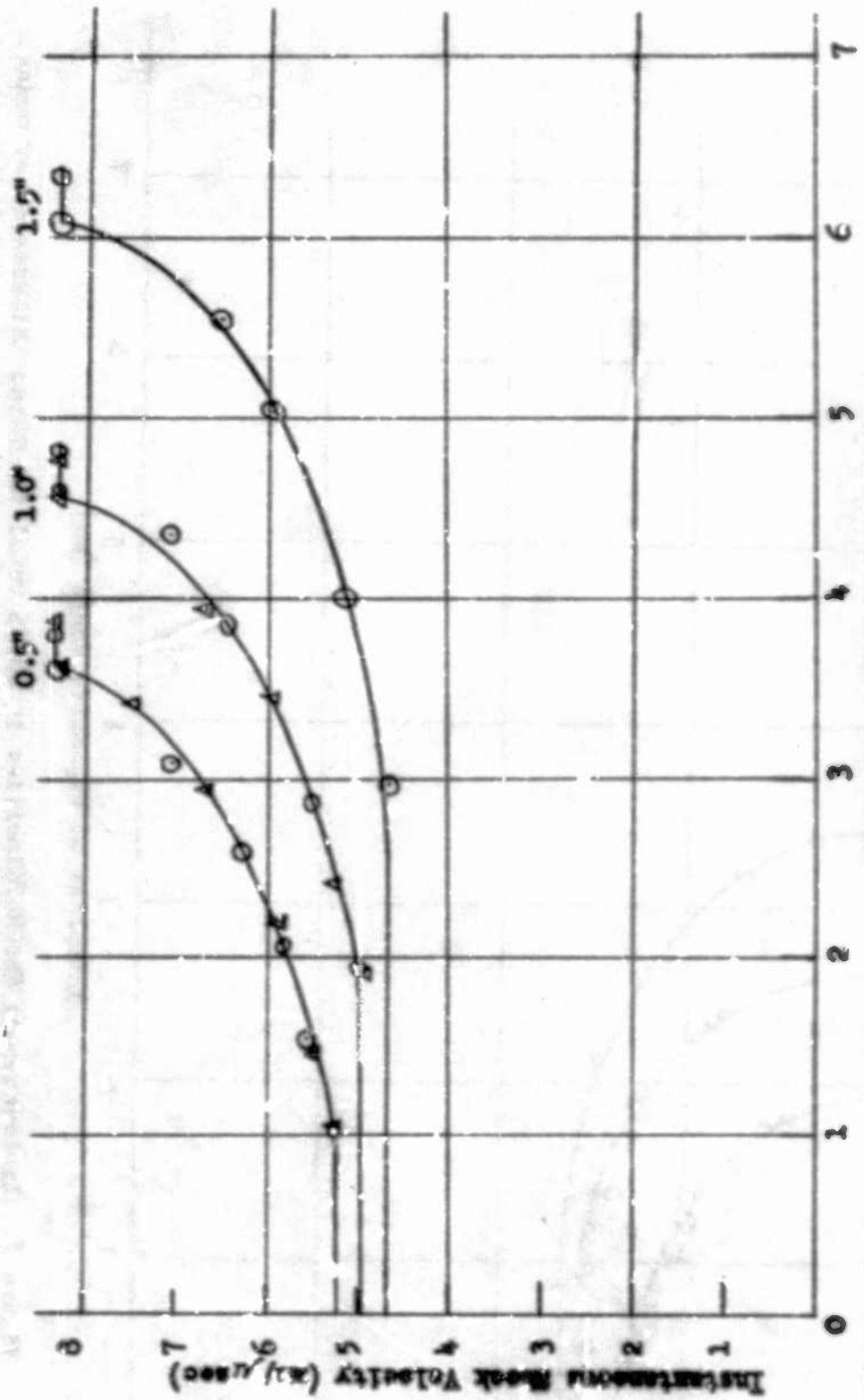


Figure 8. Instantaneous Shock Velocities in 75/25 Cyclotol for three thicknesses of brass. (Each set of circles or triangles represents an individual shot.)

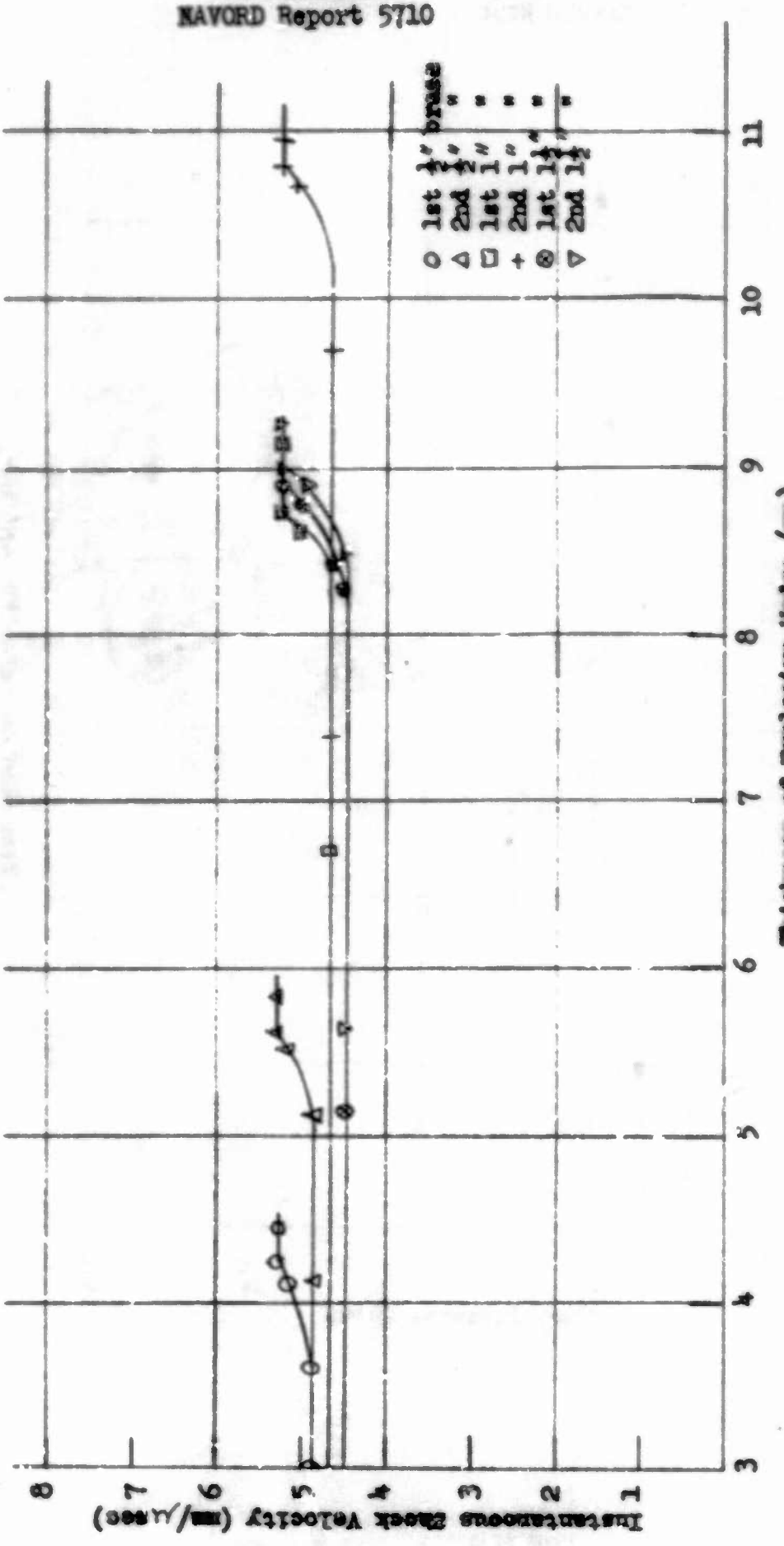


Figure 9. Instantaneous Shock Velocities in TNT for three thicknesses of brass.
(Each set of circles or triangles represents an individual shot.)

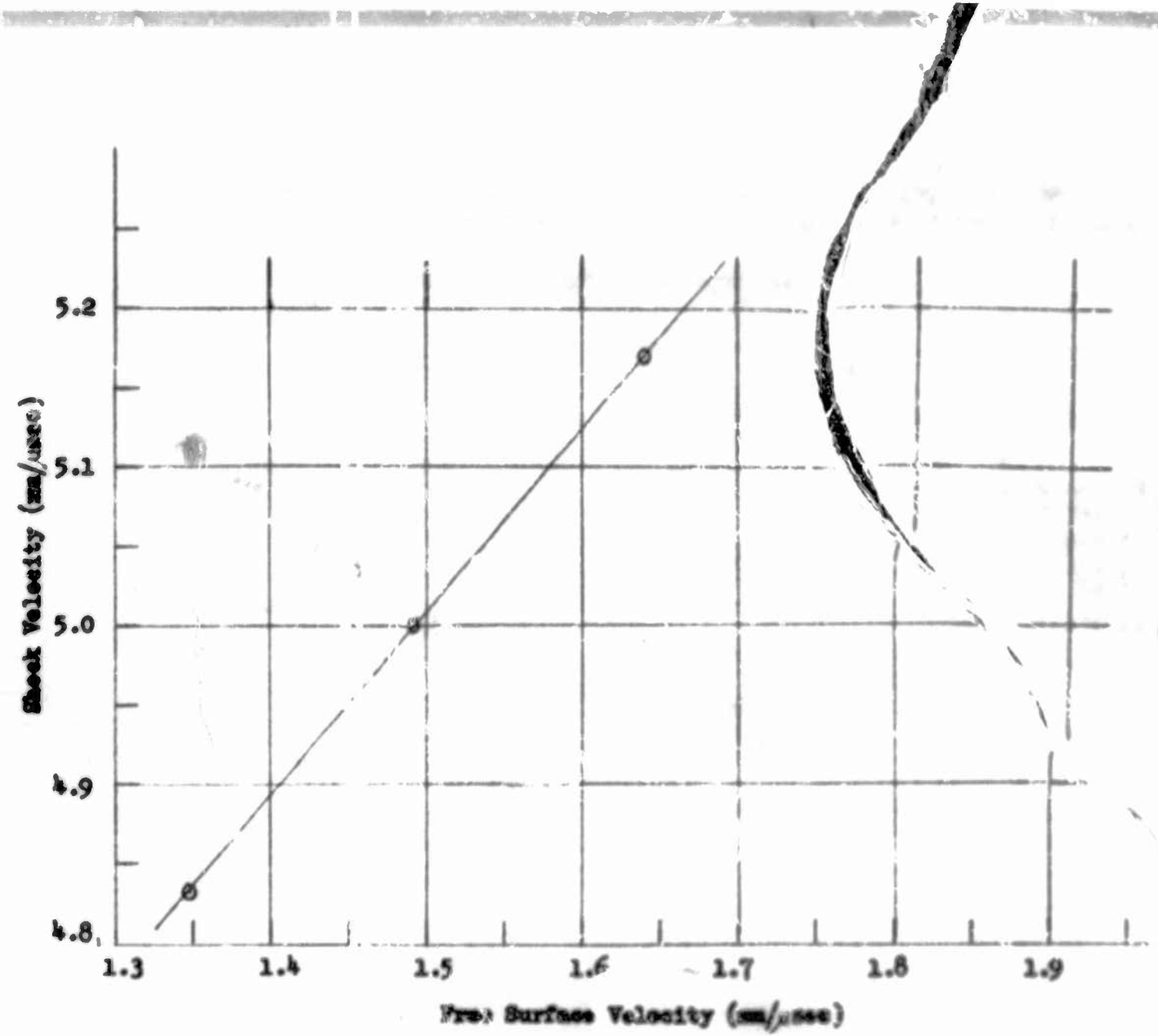


Figure 10. Free Surface Velocity as a Function of Shock Velocity in Brass Plate.

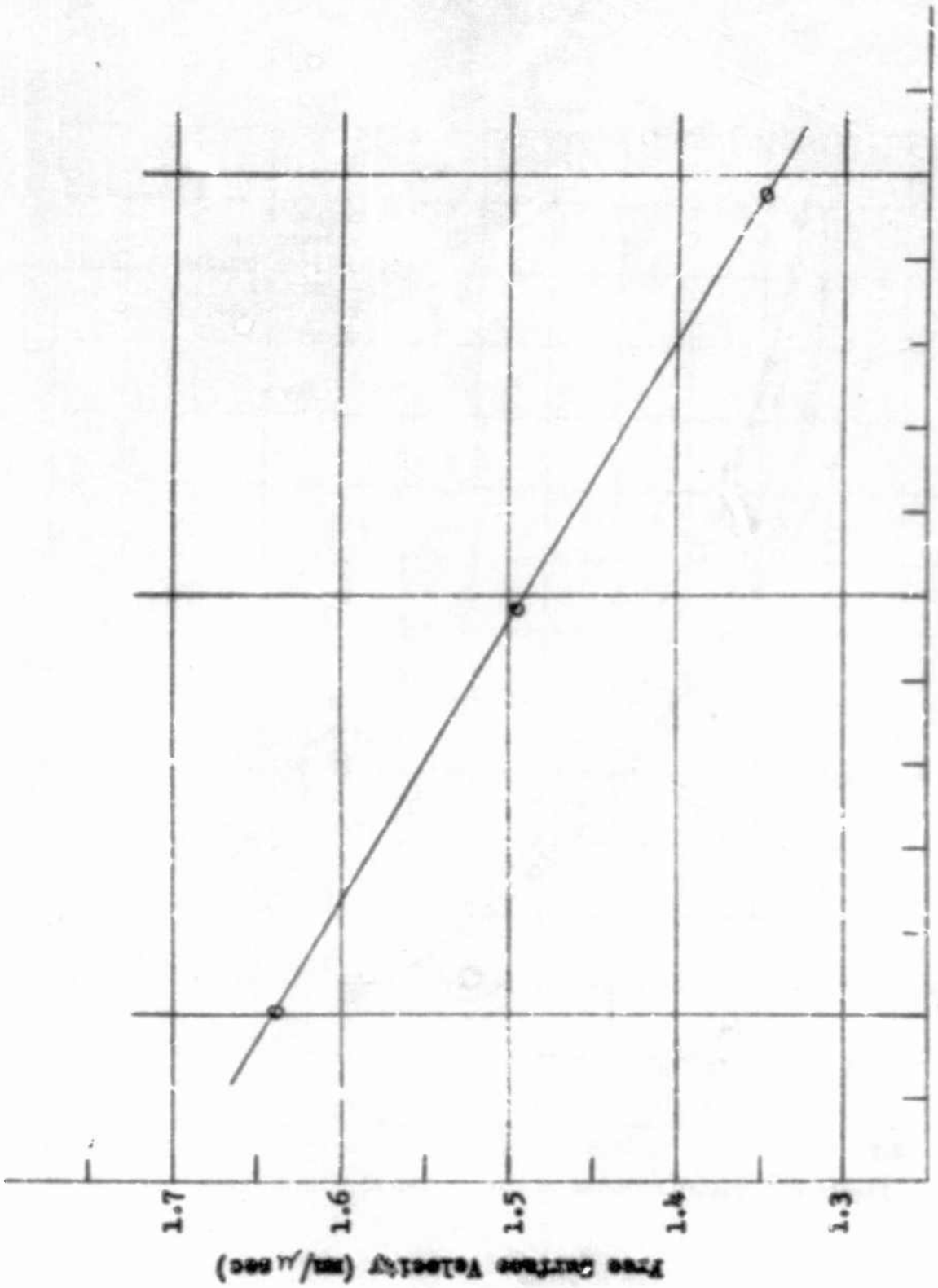


Figure 11. Free Surface Velocity as a Function of Brass Plate Thickness.

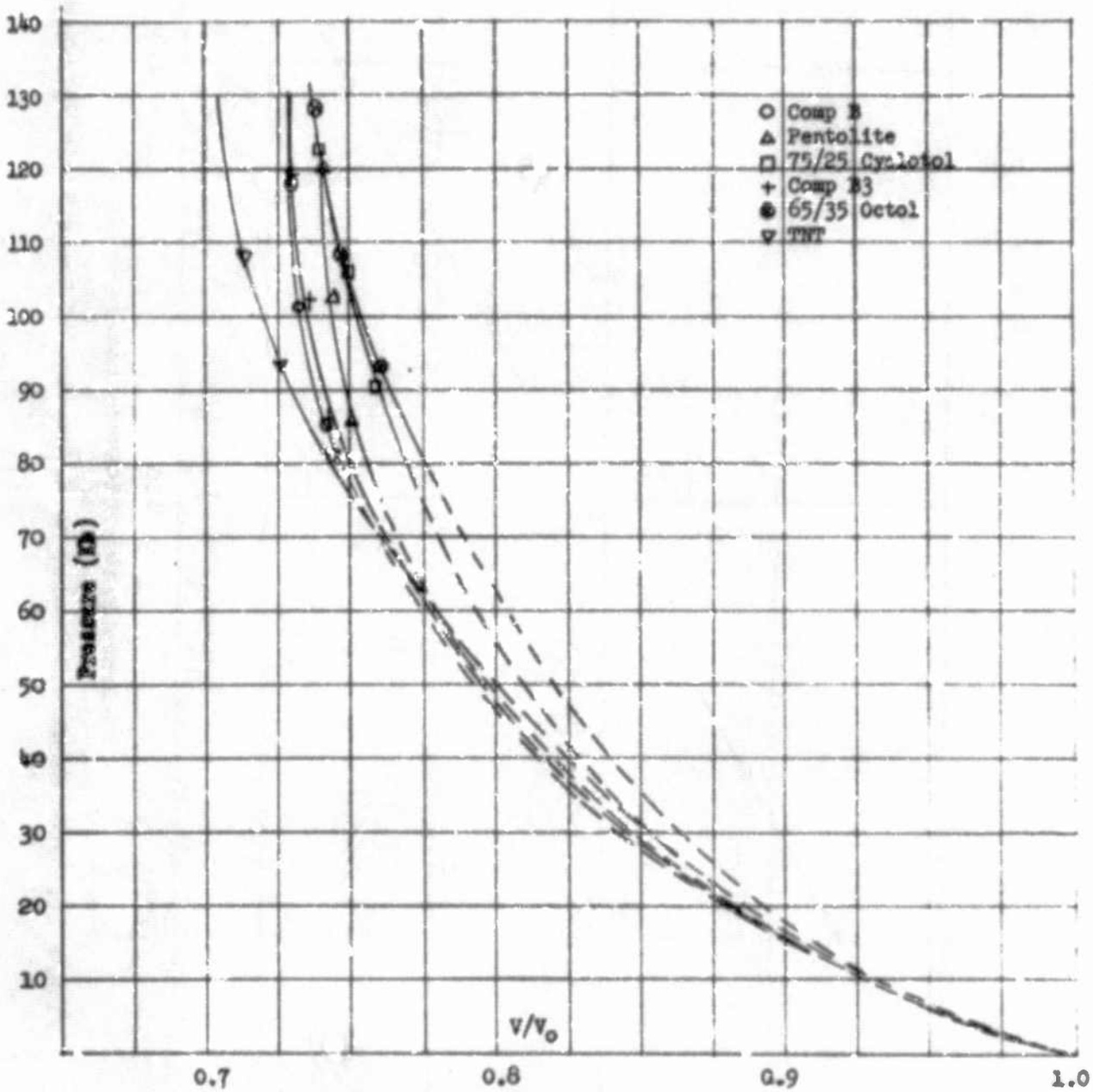


Figure 12. Hugoniot Curves for Unreactive High Explosives

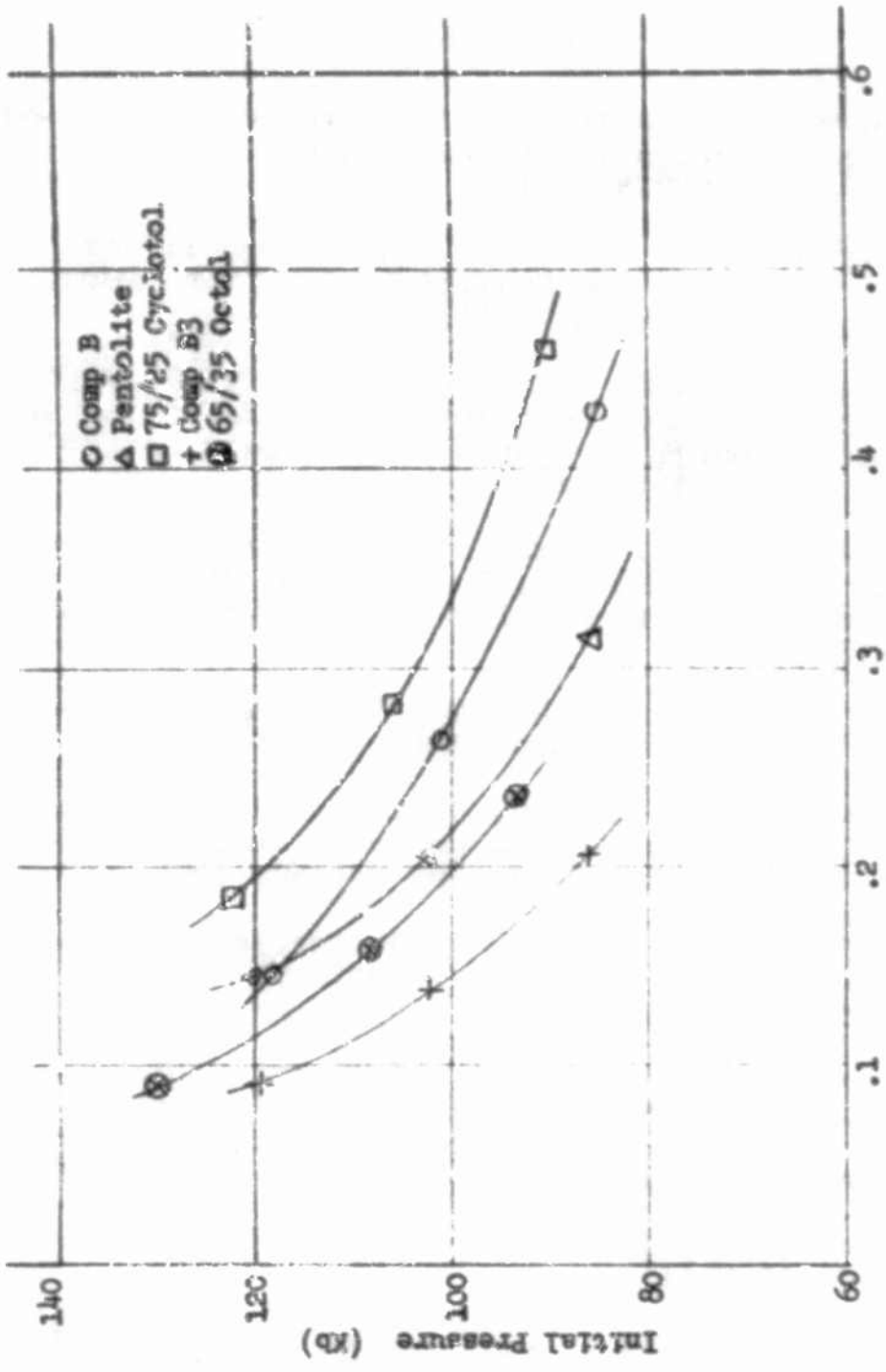


Figure 13. Delay to Detonation as a Function of Initial Pressure in Explosive.

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